Proc. Natl. Acad. Sci. USA
Vol. 79, pp. 4477–4486, July 1982
Review

Landscape evolution (A Review)

(slopes/processes/planetary surfaces/controversies/catastrophes)

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ABSTRACT Landscapes are created by exogenic and endogenic processes acting along the interface between the lithosphere and the atmosphere and hydrosphere. Various landforms result from the attack of weathering and erosion upon the highly heterogeneous lithospheric surface. Landscapes are dynamic, acutely sensitive to natural and artificial perturbation. Undisturbed, they can evolve through a succession of stages to a plain of low relief. Often, the progression of an erosion cycle is interrupted by tectonic or environmental changes; thus, many landscapes preserve vestiges of earlier cycles useful in reconstructing the recent history of Earth's surface. Landforms are bounded by slopes, so their evolution is best understood through study of slopes and the complex of factors controlling slope character and development. The substrate, biosphere, climatic environment, and erosive processes are principal factors. Creep of the disintegrated substrate and surface wash by water are preeminent. Some slopes attain a quasi-steady form and recede parallel to themselves (backwearing); others become ever gentler with time (downwearing). The lovely convex/rectilinear/concave profile of many debris-mantled slopes reflects an interplay between creep and surface wash. Landscapes of greatest scenic attraction are usually those in which one or two genetic factors have strongly dominated or those perturbed by special events. Nature has been perturbing landscapes for billions of years, so mankind can learn about landscape perturbation from natural examples.

Planet Earth and its surroundings comprise a succession of nested spheres: the ionosphere, stratosphere, troposphere, atmosphere, hydrosphere, and lithosphere, to name a few examples without penetrating to the interior spheres of the solid planet. These spheres constitute a highly differentiated system within which the interface between the solid Earth (lithosphere) and the hydrosphere and atmosphere is by far one of the most dynamic. It is at this interface that mankind lives, and the landscape he inhabits is created through the action of processes driven by energy coming both from without (exogenic) and from within (endogenic) the planet. A major part of Earth's share of solar energy is exercised along this interface, and a significant part of its internal energy is expended here in the form of volcanism, sea-floor genesis, movement of planetary plates, and other deformations of the crust. This landscape is not static, although it may appear stable to short-time observation. In geological terms, it is a highly dynamic entity, undergoing rapid and continual change.

Mankind has learned painfully that the system is highly complex, involving many variables—dependent as well as independent—and that ignorant tampering with the system can have a jack-straw effect leading to undesirable results. The building of a breakwater to create a harbor or a dam to impound floodwaters can set off a chain reaction affecting areas hundreds of kilometers distant.

Mankind is a major perturbator of the natural balance that many landscapes have attained (1–4), and concern with preserving the natural environment has focused political, commercial, and academic attention on landforms, landscapes, and the processes and conditions that create and control them. Within the context of this concern, it is important to know what the norm of landscape evolution is. In unanticipated ways, the space exploration program has independently stimulated further interest in landforms and landscape processes on Earth.

The current terrestrial landscape is largely a product of processes and conditions of the immediate past. As such, landscapes record the latest history of Earth's surface and its environments. Additionally, one of the attractive aspects of landscape study is the opportunity to observe some of these processes in action. One best understands how the lateral moraine of a glacier is constructed by watching and listening as a glacier does the job, how a river floodplain is created by witnessing a flood, how sand dunes grow by observing the wind, and how a volcanic cone is constructed by seeing an eruption. The study of landforms can be characterized as "today's geology."

Many landform processes work at rates measurable over temporal intervals, days to years, compatible with the span of individual research programs and thus allowing experiments to be established in natural settings. Although such experiments may suffer from crudity of measurements, temporal limitations, and artificial perturbations of the environment, they are usually relatively inexpensive and have yielded useful results. It would be a generous act for current landform scientists (geomorphologists) to establish experiments designed to be continued by future generations, thus spanning temporal intervals long enough to yield results not attainable within a single professional career.

The extreme complexity of processes and conditions affecting landscape evolution has caused geomorphologists to approach the subject initially by direct field study and observation. From such studies, concepts of landscape evolution have been inductively formulated. Attempts to duplicate landform developments in the laboratory suffer to some degree from the scale factors and needs of simplification to make a workable experiment. Nonetheless, useful insights and data have been obtained from such simulations (5–10), and more are to be expected as sophistication in laboratory experimentation increases. Laboratory studies of stream hydraulics have been pursued much more vigorously and successfully, but they have limited application to understanding of landscape evolution.

Construction of theoretical models as a basis for quantitative analysis of landform features has attracted considerable attention (11–20), but such efforts have met with only limited success in relation to landscapes. Again, the necessity of simplification yields a qualified result not fully applicable to the natural system. It is not yet possible to reduce landforms and landform processes to a series of theoretical formulas of wide application, and the complexity of variables within the system may, in the long run, defeat such efforts. Empirical and semi-empirical formulations do appear to apply reasonably well in some instances (21–28).

Everyone with eyesight can view the landscape, and some with perception can read the story it tells, so it is not surprising that writings on landscape evolution go back nearly 2 centuries

(29–33). Although it is possible to appreciate the beauty of landscapes without understanding their origin, it is not possible to live in greatest comfort and safety within a landscape without understanding its genesis and evolution. This understanding is one of the principal goals of geomorphology. Actually, many of the most interesting landscapes are those in which some factor of landform genesis has exercised a dominating control or those in which normal evolution has been interrupted or perturbed by some special circumstance.

Landscapes are made up of assemblages of landforms, and landforms are bounded by slopes of various sizes, shapes, patterns, and declivity, ranging from vertical to horizontal. A flat is simply a slope of zero declivity, but how it got that way makes an interesting story. Thus, landscape evolution is best understood through a knowledge of slopes—their origin and evolution and the processes and conditions that control them.

SLOPES

The literature on slopes is voluminous (4, 16, 20, 32–36), but digests and summaries are available (18, 20, 37–42). The following is a treatment of basic factors and considerations influencing slopes, subjectively filtered through a background of personal experience and observation. Although slopes may exist in quasi-steady form (14, 43–49), they are never truly static in a geological sense. They are constantly changing in size and location, and almost nothing seems sacred in the realm of slope evolution.

Formal classification of slopes and slope elements (18, 50, 51) need not be of great concern here. Identification of a few slope types and characteristics will serve our needs adequately. Some slopes are primary, having been created in their present form principally by endogenic processes such as faulting, folding, warping, or volcanism. Shapes of primary slopes are quickly modified by exogenic processes, so they rapidly become secondary in form. Most slopes are secondary from the start, because they are shaped from the beginning by exogenic processes. Secondary slopes are largely of erosional origin—for example, the wall of a stream-cut canyon—but a modest number are constructional, being built by deposition of debris derived from erosional slopes. Erosional and depositional slopes are commonly closely associated, an example being a depositional alluvial apron lying at the base of an eroded mountain face. Some slopes expose bare bedrock, whereas others are mantled by disintegrated rock debris (regolith). Although many slopes display a combination of bedrock outcroppings and regolithic accumulations, it is useful to speak of "bedrock slopes" compared to "detrital slopes" in instances in which one or the other state dominates.

Because erosion plays a major role in shaping slopes, it is reasonable to speak of "wash slopes" (those on which the work of surface water predominates) and "gravity slopes" (those shaped primarily by the downhill creep of loosened debris *en masse*). "Supply slopes" are those from which debris is derived; "transport slopes" are those across which the debris moves; and "accumulation slopes" are those on which debris is deposited. In regard to declivity, supply slopes tend to be steep, transport slopes are of near-uniform and gentler declivity, and accumulation slopes are still gentler, usually decreasing in declivity downhill. Supply slopes commonly are largely bare bedrock, transport slopes are mostly mantled by a thin but continuous blanket of debris (regolith) in transit, and accumulation slopes are underlain by much thicker deposits of detritus which may be undergoing only slow creep under gravity. The supply slope is dominated by erosion, and some erosion may occur on transport slopes.

The profile geometry of slopes invites description. Some are nearly rectilinear—that is, of essentially uniform declivity—and others are curved, either convex or concave to the sky. Convex slopes are usually dominated by erosion, rectilinear slopes are primarily transportive, and concave slopes can be either erosional or depositional, frequently the latter. The combination of convex, rectilinear, and concave elements into a smoothly integrated slope profile (Fig. 1) constitutes one of the more graceful and pleasing geometrical forms of natural landscapes.

Landscapes are most commonly viewed in profile, hence the preoccupation with slope forms. However, slopes also produce interesting planimetric patterns when viewed from above, and, in this day of satellite images and high-flying planes, such patterns attract attention. Planimetric patterns created on homogeneous materials respond well to quantitative analyses (21, 23–25, 27), but most earthly settings of more than modest extent are not homogeneous, and the inhomogeneities of the underlying substrate exert a strong influence on landscape patterns.

Barring interruptions, from endogenic events or environmental change, the molding of slopes by exogenic processes can progress smoothly and gradationally through a succession of changes to a destined end, a surface of low relief (52–54). However, the vagrancies of nature are such that a smooth progression is interrupted more often than not, so that many landscapes are composed of more than one generation of slopes. It is this combination of vestigial slope forms that enables students of landscape to decipher the recent geological history of an area. Many processes and conditions play a role in determining the character and evolution of slopes. Some of the factors, such as the substrate, are passive, but most are active and many are interdependent.

Substrate or Bedrock. Materials composing the lithospheric surface are highly heterogeneous; the remarkable differentiation of earthly materials is nowhere more strongly developed than on the planetary surface. This heterogeneous mixture interacts in complex ways with weathering and erosive processes, and the diversity of natural landscapes reflects these relationships.

It is desirable to differentiate between weathering and erosion, a distinction not always clearly or rigorously drawn even in professional literature. For our purposes, weathering involves the chemical and physical interaction between materials of the lithosphere and the atmosphere, aided by elements of the biosphere. The result is a product consisting of decomposed and disintegrated substrate rocks and minerals known as "regolith," a handy term. New chemical compounds may be formed—for example, clay minerals—or the rocks and their component minerals may simply be broken up (disintegrated). Although disintegration is physical in nature, it most commonly results from chemical rather than mechanical weathering. Only in special environments is purely physical breakup of rock—for ex-

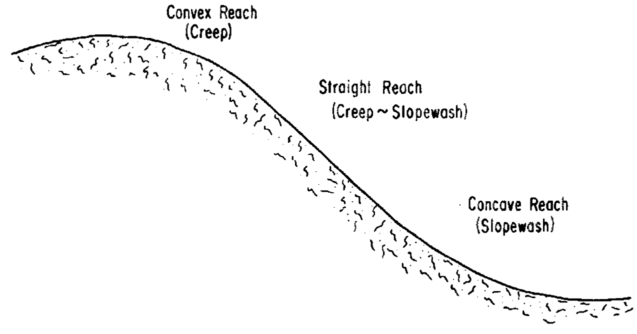

FIG. 1. Compound slope profile on which creep dominates the convex reach, surface wash dominates the concave reach, and creep and wash are roughly balanced in the straight reach.

ample, by freeze and thaw—likely to be important. Insofar as slopes are concerned, erosion involves principally the entrainment and removal of regolith. On slopes it is primarily a transportive process because abrasion by the transporting medium is minor on most slopes, except possibly for wind and avalanches under some circumstances.

The caliber of debris produced by weathering is usually considered a prime factor in determining slope declivity (20, 55, 56). A substrate that yields fine, even-grained detritus generally produces gentler, straighter, smoother slopes than does a substrate weathering to a wide spectrum of particle sizes. As always, there are exceptions (57), and in certain environments very fine uniform debris can stand in extremely steep slopes (58). In terms of large landscape entities, especially planimetric patterns, the structure of substrate rocks can be a dominating influence (20, 59). The striking terrain of plateau regions featuring tablelands, mesas, buttes, cliffs, benches, and spires is controlled by horizontal layering within an inhomogeneous sequence of sedimentary strata, such as shale, sandstone, and limestone. The totally different planimetric configuration of terrain within the Appalachian Mountains reflects the folded nature of an equally diverse sedimentary sequence. The substrate can and does exercise a dominant influence on many landscapes.

Biosphere. The biosphere is a powerful but dependent variable within the complex of factors affecting slope development. It is strongly controlled by climatic environment and so much affected by the substrate that, to some degree, it can be regarded as an intermediary factor passing along messages from these two sources. Even within a single area, slopes underlain by shale are likely to be grass-covered and those underlain by sandstone are more likely to bear a cover of brush, shrubs, or trees. It is often possible to make a generalized map of the bedrock by outlining the different areas of vegetation. The contrast between steep, barren slopes of a badland and subdued, gracefully rolling hillsides of areas in Wisconsin, Missouri, or Ohio reflects largely a biospheric influence. It is possible to have, temporarily at least, badland terrain even in Wisconsin, if vegetation can be eliminated.

Delivery of rainfall to the ground surface under a cover of vegetation involves such variables as through-fall, drip, and stem flow. Protection of the ground by litter, binding of the regolith by roots, and enhancement of the all-important factor of water infiltration into the ground are other biospheric influences.

Grass exercises a particularly effective role in slope development: it can protect the slope completely from the powerful process of raindrop impact; grass stems dispense the surface runoff and delay development of channelized flow; grass roots are effective in binding the upper part of the regolith; and the infiltration rate can be even greater on grass-covered than on barren soil (60). Greater infiltration decreases erosion by runoff and enhances the work of subsurface water. Although grass roots may bind the regolith, they seldom anchor it to the substrate, as do some tree roots. Thus, in the face of reduced surface runoff, greater subsurface water, and the lack of anchoring, it is not surprising that grass-covered slopes experience considerable mass movement, largely by creep.

Organic acids, supplied by decomposed vegetation, promote rock and mineral weathering, and each vegetative complex brings its own microfauna which contributes both to weathering and to soil creep. The possible role of microfaunas in slope development has not yet been fully evaluated. The influence of macrofaunas such as burrowing rodents or trampling hoofed animals is widely recognized as helping determine the microtopography of slopes. The regolith on a slope richly inhabited by burrowing earthworms must experience more rapid downhill creep than a wormless slope. This is a topic not yet investigated quantitatively, perhaps out of fear of winning one of Senator Proxmire's Golden Fleece awards, even though creep is widespread on many Wisconsin slopes and can have local economic impact.

Climatic Environment. Climate, through its control of the biosphere and its influence on the nature, power, and effectiveness of weathering and transporting processes, plays such an obvious role in slope evolution (20, 49, 50, 61) that it is only treated briefly here. Slopes and landscapes of arid regions contrast distinctly with corresponding features in humid regions (49, 50, 62, 63). A homogeneous, coarse-grained, igneous rock yields slopes in the Mojave Desert notably different from slopes developed on a corresponding rock in Wisconsin.

An aspect of the environment, perhaps not yet fully appreciated, is microclimate (64, 65). The differences in north- and south-facing slopes, widely recognized within local areas (49, 64, 66), are largely a product of microclimate, exercised through its control of the biosphere and slope processes. This relationship is reasonably obvious, but more subtle influences on an even smaller, more local scale may be exercised by microclimatic differences controlled largely by small-scale topographic configurations. This is a matter possibly worthy of greater attention.

Slope Processes. Unless the underlying substrate is unconsolidated, the development of what might be termed "adjusted" or "graded" slopes begins with weathering of the substrate. In most regions this weathering is predominantly chemical. Slope evolution naturally proceeds more rapidly on materials easily susceptible to weathering than on a resistant substrate. Weathering is a subtle, delicate process capable of exploiting minor inhomogeneities of material that escape macroscopic human observation. Once particles are loosened from a consolidated substrate by weathering, surface erosion begins. Most erosion on slopes results from two processes, surface wash accomplished by water delivered to the slope largely by rainfall, and creep accomplished through the slow downslope movement of regolith by gravity. Creep is a form of mass movement; other examples common on slopes are landslides and earthflows. These last two phenomena can seriously perturb and shape a slope (67), but they are dominant only locally or in special situations.

The first phase of surface wash or sheet erosion (21, 68–70) is accomplished by raindrop impact, a remarkably powerful process on barren slopes (69, 71–73). Although the splash associated with raindrop impact moves material upslope as well as down, the net effect is a significant downslope movement. On the uppermost reaches of slopes, where runoff from higher reaches is not a factor, the water from raindrops initially gathers into little threads flowing among particles, grass stems, and irregularities of the ground surface. Thread flow is capable of carrying only fine material, but aided and abetted by raindrop impact, which creates turbulence and helps entrain material, it can accomplish some erosion. If rainfall is heavy and infiltration rates are modest, the individual threads can grow and merge to form a sheet of water—so-called sheet flow. Sheet flow, again aided by raindrop impact, is a more effective transporting agent than thread flow.

Whether thread flows merge to form sheets or not, they eventually coalesce to form small, parallel, subequally spaced streamlets that carve little emphemeral channels (rills), usually uniformly a few centimeters deep and wide. This happens if water supply is great enough and the slope steep enough, and it is the initial occurrence of channelized flow. Rills are a more effective erosive agent than thread flow or sheet flow and are credited by some investigators with causing a steepening of the slope (74–77). This is a debatable matter because rills more often appear to adapt themselves to the declivity of a slope than to create that declivity. Eventually, rills become integrated, and the larger discharge carves gullies, usually in a tree-branch planimetric pattern. The discharge down gullies is a far more powerful erosive agent than the earlier forms of flow, and its localization soon leads to dissection which causes a reorientation of slopes toward gully lines.

Infiltration capacity (the capacity of regolith to take up water) and infiltration rate (the rate at which water percolates through the regolith) are important factors in slope development that probably could benefit from even more consideration and measurement than already accorded (21, 58, 60, 65, 72, 78–80). Slopes on highly pervious materials, with high infiltration capacity, are generally steeper, other considerations being equal, than slopes with low infiltration capacity. Infiltration on slopes creates and maintains a supply of subsurface water. The role of this subsurface water in weathering and vertical and lateral transport of fine particulate debris (eluviation), promotion of mass movements (creep), and feeding of surface seeps and springs has deservedly received considerable attention (42, 68, 81–83). In some situations, subsurface water may remove more material from a slope by solution than all other processes combined (84), and the role of lateral (downslope) eluviation, the subsurface transport of fine particles, merits further consideration.

The other principal process of slope erosion, creep, involves a slow, pervasive, downslope movement of the regolithic mantle, imperceptible to short-time human observation but measurable in terms of its effects on older human structures—for example, gravestones. Creep involves primarily the downslope shifting of particles within the regolith, and anything that disturbs those particles, such as vibrations from microseisms or freeway traffic, earthworms, plant roots, wetting and drying, heating and cooling, or freezing and thawing, contributes to the phenomenon. Although creep can occur within the debris mantle on any part of a slope, it is probably the dominant process of erosion on the uppermost reach, where surface wash (overland flow) has not yet attained a volume large enough to be at major effectiveness. Velocity of creep can increase downslope owing to steeper gradients, more abundant subsurface water, and, possibly, finer grain within more weathered regolith, although it is yet to be demonstrated that regoliths generally become finer downslope (19, 85).

CONTROVERSY

Things are seldom all sweetness and light in any scientific field, and landscape evolution is no exception. Some examples of controversy follow.

Convex Summits and Divides. Most ridges and peaks in deeply dissected, rugged mountains are narrow and sharp, dropping away directly to steep bedrock slopes, but the summits and ridges of lower, regolith-mantled, hilly landscapes are commonly broad and smoothly rounded. It is in such terrains that the graceful convex/rectilinear/concave hillside profiles (Fig. 1) are seen. It is a simple task to deduce a half-dozen different ways for producing rounded divides and summits. However, the rounded divides of most regolith-mantled hillslopes seem to have evolved from the normal progression of weathering and erosion without intervention of abnormal outside influences or events or an interrupted history.

Most hillslopes have been initiated by stream dissection of elevated areas, and at some early stage of their development, especially in homogeneous material, they were probably rectilinear from top to bottom. Divides between such slopes are initially narrow and sharp. Thus, it is reasonable to analyze development of convex divides by starting with a rectilinear slope

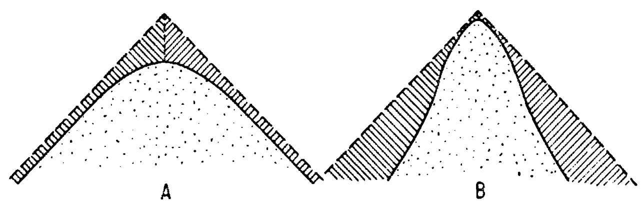

FIG. 2. Convexity produced by greater erosion at the top (A) or greater erosion downslope (B). Declivities are exaggerated by larger verticle scale. ▨, Material removed.

rising to a sharp divide. Convexity on such a slope can be created by gentling of the uppermost reach (86–91) or steeping of the slope downhill from the divide (21, 50, 74–76, 92–96). The rounding is more easily accomplished with less work by removing a lune-shaped segment at the top (Fig. 2A) than by erosional steepening of the side of the slope (Fig. 2B). The breadth of rounded divides is also more easily produced by gentling at the top.

Simple geometrical measurements should help resolve this matter. If gentling has occurred, then no part of the convexity should have a declivity greater than that of the slope immediately below. If a rectilinear slope element succeeds the convexity, a common occurrence, the declivity of the rectilinear element should be approximately the same as the steepest part of the convexity (Fig. 2A). If the convexity is created by steepening, then the rectilinear slope succeeding the convexity should be of gentler declivity than the steepest part of the convexity (Fig. 2B). This second relationship is seen on slopes with a free face—that is, a steep face from which debris is shed onto gentler slopes below (Fig. 3). However, such free faces commonly reflect perturbations introduced by the substrate, a slide, or an interrupted cycle, and most classical convex/rectilinear/concave slopes do not display them. That a free face can be created on regolithically controlled slopes by localized rill erosion (74–76), in any other than exceptional situations, is debatable. For these reasons, favor generally rests with gentling of the crest by erosion as the means of creating convexity.

The proponents of this view, however, do not agree as to whether the dominating erosional mechanism is surface wash or creep. Because the topmost unit of a slope does not receive debris from higher slope units, the substrate there is more susceptible to weathering and erosion than are other units on down the slope. This reasoning can be extended incrementally downslope to where the problem quickly becomes one of accommodating the increasing discharge of debris rather than eroding the substrate. This discharge includes not only the product of weathering under the incremental unit concerned but also the debris received from all units on an orthogonal line higher up slope. If a slope is not to become solely one of accumulation, an increasing discharge of debris must be accommodated downslope.

The effectiveness of surface wash increases with increasing volume of water and as the mode of flow changes from thread flow to sheet flow to channelized flow. Most slopes with prom-

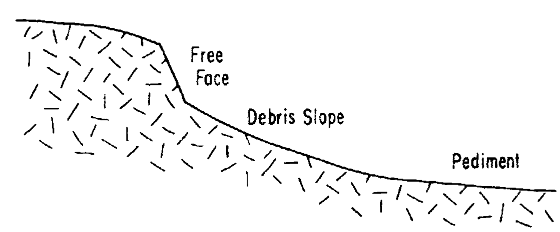

FIG. 3. Compound slope profile with a free face. [After Wood (74).]

inent summit convexity are grass-, brush-, or tree-covered, so raindrop impact may not be of much import in their evolution. If gentling is the cause of convexity, then the greatest erosion of the substrate has occurred at the point where surface wash is least effective, the crest of the divide. This suggests that creep is the dominant mechanism for debris removal there. Creep has a further advantage over slope wash in that it can increase its discharge downslope simply by increasing the thickness of the mobile regolithic mantle. Velocity within this mantle, the other parameter controlling discharge, may also increase downslope owing to greater fineness of debris produced by longer weathering, more subsurface water resulting from infiltration, and, probably most important, the natural increase of declivity toward the inclination of the initial rectilinear slope. Both slope wash and creep can operate on the convex part of a slope, but creep is probably the dominant mechanism. It is a fact of general observation and some measurements (19) that thickness of the regolithic mantle does increase downslope under some convexities, but this relationship deserves more study.

The normal graded profile produced by running water is concave skyward, and the lower concave reach of compound slopes (Fig. 1) is generally regarded to be shaped by surface wash. The rectilinear reach intervening between the concave and convex reaches seemingly is a zone over which the supply of debris and the processes transporting it are nearly balanced so that no significant change of declivity is required to handle the discharge. The tendencies toward convexity and concavity mingle and are seemingly about balanced within this rectilinear reach.

Slope Evolution. Disagreement exists as to whether slopes evolve through a succession of more or less steady-state forms, gentler slopes replacing steeper slopes (75, 76, 93, 94, 97), or whether slopes just become gentler with age and progression of the cycle of erosion. In an oversimplified way, these two possibilities can be characterized as the concepts of backwearing and downwearing.

At the turn of the 20th century, W. M. Davis (98) proposed a scheme of landscape evolution in which an uplifted landmass of gentle relief was rapidly dissected by streams into a complex of deep, narrow canyons and sharp ridges. This landscape, according to Davisian concepts, was then worn down by weathering and erosion with the slopes becoming progressively ever gentler. The end product was a new and lower surface of gentle relief graded to an ultimate base level of erosion, the sea. This predominantly erosional plane, or near-plain, was termed a "penelain" (52). Walther Penck (99) and others (75, 100, 101) have maintained that plain-like erosion surfaces are formed not by downwearing but by backwearing through the retreat of steeper slopes which maintain a relatively constant form as they recede. Pediments—smooth bedrock erosion surface of gentle declivity lying at the base of steep mountain faces in arid regions—presumably are of this origin (100). Whether the concept

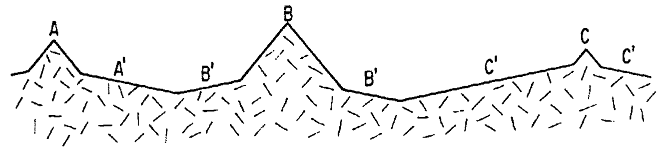

FIG. 4. Extensively eroded, homogeneous, coarse-grained, igneous rock in an arid region. Residual peaks of different sizes all are defined by slopes of similar declivity. Primed letters identify the pediments flanking the peaks.

of slope recession can be extended to the compound slopes of humid regions is affirmed by some and denied by others.

It is now recognized that the apparent conflict between the proponents of backwearing and downwearing has been grossly overemphasized, even overdramatized (20, 102). Evidence for both can be found in natural settings. For example, in areas of extensively eroded, homogeneous, coarse-grained, granitic rock in arid regions, the residual hills, peaks, or knobs, both large and small, are defined by slopes of similar declivity, although they have obviously experienced different amounts of recession as shown by the extent of flanking pediment surfaces (Fig. 4). Elsewhere, as in the Yosemite region of California's Sierra Nevada (Fig. 5), remnants of older landscapes strongly suggest that slopes do get gentler as an erosion cycle proceeds (103). Progressively older valleys are bounded by increasingly gentler slopes, and there is no evidence that this relationship involves replacement of receding steep slopes by gentler slopes.

In humid regions, the nature and behavior of the regolithic mantle are major factors determining the form and evolution of slopes. Grain size within the regolith should change with time, becoming progressively finer and more clay-rich downslope with longer exposure to weathering, although this has not been wholly confirmed by initial studies (19, 85). Such changes would favor increased mobility for both surface wash and creep and, as mobility increases, a decreased slope declivity could possibly handle the downslope discharge of debris. It seems almost inevitable that, barring accidents or special conditions, these influences would lead to a gradual gentling of slopes throughout an erosion cycle.

Both backwearing and downwearing of slopes appear to occur, probably in both arid and humid environments, but with a difference of emphasis. Under favorable lithologic, structural, and topographic conditions, backwearing can dominate in an arid environment, but it is by no means universal. Remnants of relict landscapes suggest that downwearing can dominate in some humid areas, although backwearing probably occurs, too. That regolith-mantled slopes recede parallel to themselves, maintaining a steady-state form, in humid regions, to the same degree as barren rock slopes do in arid regions has yet to be

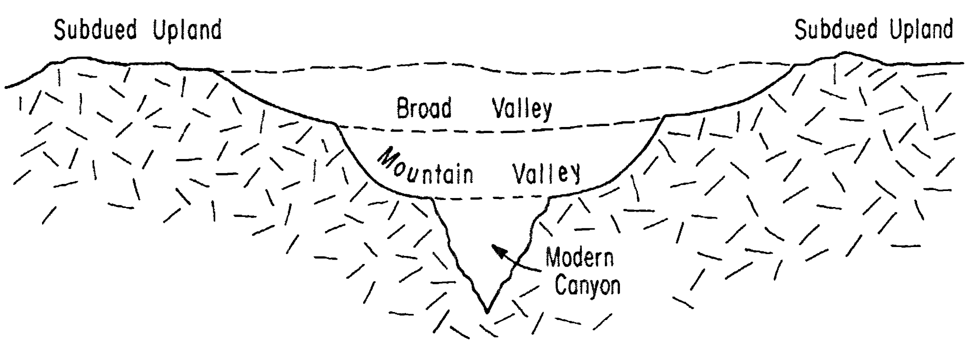

FIG. 5. Successively older valleys with increasingly gentle side slopes in Yosemite region (California). [Adapted from Matthes (103).]

demonstrated to everyone's satisfaction, although the idea has its proponents (50, 77, 101, 104).

LANDSCAPES AND PLANETARY EXPLORATION

One of the most striking, voluminous, and useful products of the space exploration program is the photo imagery of the surfaces of Moon, Mars, Mercury, and satellites of Jupiter and Saturn. Although features of these extraterrestrial landscapes differ in character and scale from earthly forms, enough similarities exist, especially for Mars, that terrestrial knowledge greatly aids in their interpretation. Reasoning by analogy in such instances has its dangers and weaknesses (105), but it is still the best game in town. A sand dune on Mars looks like a sand dune on Earth, and patterns made by martian dunes are similar to earthly dune patterns (106). The unquestioned recognition of volcanic features on other planets has been possible because of our understanding of volcanic forms on Earth.

The benefits are by no means one-sided, because features seen on other planets have stimulated greater interest and research on certain earthly processes. The huge channels of the martian surface have rekindled interest in the evidences of gigantic water floods on Earth, the Spokane Flood of eastern Washington State being the prime example (107–111). This subject was formerly one of great controversy (112–116) which has now apparently been resolved in favor of the occurrence of such events, partly because of the renewed interest generated by problems on Mars (117–119).

The possibility that much of the missing water of Mars is locked up in bodies of subsurface ground ice (120–122) has sparked interest in phenomena related to perennially frozen ground and ground ice on Earth. These topics were heretofore largely relegated to engineers and students of high-altitude and high-latitude environments (123, 124). Features on Mars that look like they might have been formed by ground-ice deterioration are much larger, more complex, and more widely distributed than features of such origin on Earth, suggesting that ground ice is a more important phenomenon on Mars (125–133). The large-scale and abundant evidence of collapse over huge areas within the equatorial region of Mars has no recognized analog on Earth and may never have occurred here.

Sapping, a process that undermines slopes and cliffs by differential weathering or ground-water seepage, has long been recognized on Earth (81, 97, 134–140) but heretofore has not been accorded the attention it deserves. Owing to the abundance of landforms on Mars possibly created by sapping (119, 126, 141–143), that situation is rapidly changing (ref. 140; unpublished data). Much of the martian sapping may have been caused by evaporation of exposed masses of ground ice (121, 126, 127) rather than by ground-water seepage. On both Mars and Earth, a major concern has to do with the disposal of rock debris produced by sapping, a problem not yet fully solved for either planet.

Wind is clearly one of the processes currently active and effective on the martian surface (129, 144–152). Studies of eolian activity on Earth have focused largely on mechanisms and products of transport and deposition. The possibility that long-continued wind erosion has played a significant role in the creation or modification of martian landforms has stimulated interest in earthly features created by eolian erosion (153–156).

Earth is richly endowed with effective erasing processes—such as weathering, erosion, and deposition—which are weak or lacking on other planetary surfaces, except possibly on Venus. As a result, the writings on extraterrestrial blackboards are more cumulative and enduring. Fossil landscapes abound on Mars, from which one has opportunity to recover records long since erased on Earth. On Mars, it is also possible to observe the cumulative effects of a single process acting for a long time without serious interference from other processes, a privilege rarely accorded on Earth.

Space exploration has increased interest in some processes nominally relegated to a minor role in landscape evolution on Earth, meteoroidal impacts being an example. The overwhelming abundance of impact scars on other planetary surfaces has caused us, with benefit, to look at various unusual features and structures on Earth as possible products of such impacts (157–161). Images of the martian surface have also revealed features and patterns unlike anything yet recognized on Earth (130, 156, 162–164). It may be that we have not yet looked at all terrestrial landscapes with the right pair of glasses. Hopefully, the martian features may cause us to do so.

PERTURBED LANDSCAPES

Although the normal uninterrupted evolution of slopes produces landscapes pleasing to human eyes, much of the spectacular scenery that mankind dedicates as monuments and parks is the result of perturbations of the normal cycle or the dominating influence of one or two of the many factors affecting landscape development. Monument Valley (Arizona, Utah, New Mexico) reflects the dominating control of horizontal stratification within a heterogeneous pile of sedimentary beds, aided and abetted by sapping. The Grand Canyon is spectacular solely for its size and depth, but the landscape elements of its walls, such as box-head canyons, spires, temples, and buttes are what give the Grand Canyon its special flavor. They are the product, largely, of differential sapping acting on a near-horizontal heterogeneous sedimentary rock sequence. The Jackson Hole–Teton scene (Fig. 6) in Wyoming results from the predominance of faulting and glaciation over other land sculpturing processes. The domes, cliffs, and waterfalls of Yosemite (California) reflect the dominating influences of glacier erosion and a massive, homogeneous bedrock. Bryce Canyon (Utah) by contrast, demonstrates the power of rainbeat and surface wash on soft, fine, but coherent, sedimentary rock. Karst topography (165, 166), such as the pepino hills around Kweilin, now viewed with wonder by American visitors to China, are the product of groundwater solution. The ocean can be regarded as a great pool of energy, for it intercepts nearly 70% of the solar radiation coming to Earth. The expenditure of some of this energy along the contact between the ocean and land dominates the landscapes of shorelines (167). The high, steep cliffs of a coast reflect the concentration of this energy, delivered largely by waves along a horizontal plane intersecting a sloping landmass and give a measure of the retreat of the land under that onslaught.

Many landscapes have been perturbed by climatic change or tectonic events. One of the principal tenets of Walther Penck's (99) geomorphology was that tectonism and slope degradation could work hand in hand in determining the form of the slope by gradual evolution. Schumm (168) challenged this concept by showing that the average rate of tectonic uplift so far exceeds the rate of down cutting by erosion that the effect of tectonic activity on landscape evolution is more episodic than evolutionary. An example of the effects of episodic tectonism is provided by the old valleys of the Yosemite region (Fig. 5) which are attributed to repeated uplifts of the Sierra Nevada fault block (103). Many modern landscapes preserve vestigial remnants of early landscapes, and if the scale of these relationships is extensive, the cause is most likely episodic tectonism which has interrupted the progression of earlier erosion cycles.

On a finer scale, climatic variations are capable of perturbing the normal progression of landform development. As one moves down the scale of size, more and more influences are capable of such effects. For example, a terrace along a stream could re-

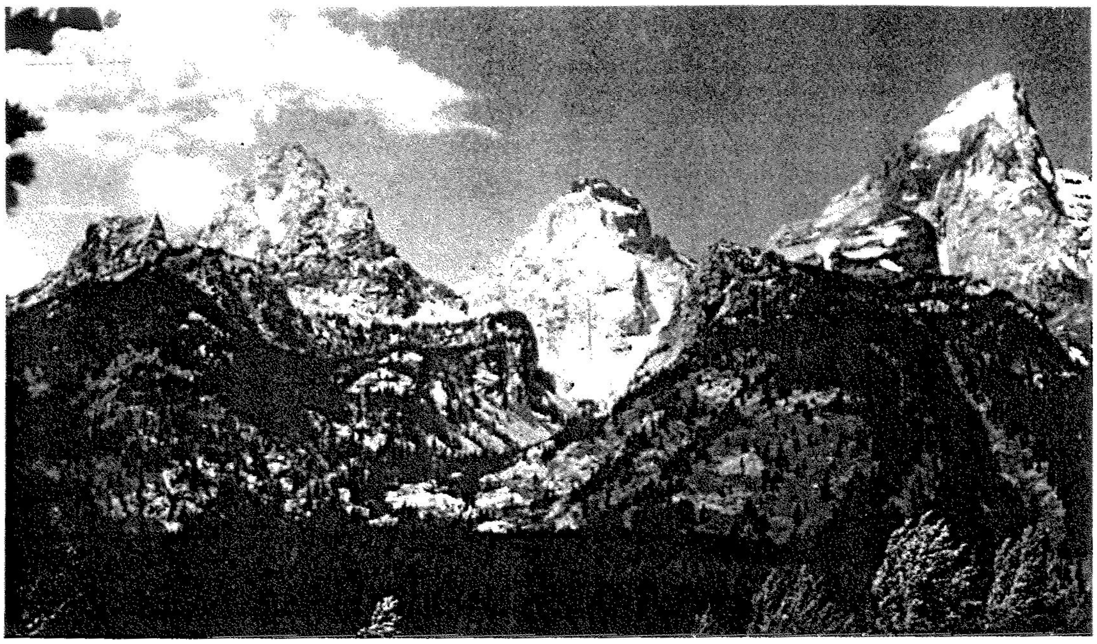

FIG. 6. East face of Teton Range (Wyoming), a landscape dominated by faulting, glaciation, and a crystalline substrate.

flect a change in stream character that might have been caused by climatic change, fluctuation of a glacier in the headwaters, a large landslide, stream capture, or activities pursued by mankind such as grazing, deforestation, and dam building.

Landscapes are sensitive and perceptive, and mankind has learned, bitterly, just how subtle these sensitivities can be to the perturbations introduced through his activities. It is to mankind's self-interest that someone be able to read the history of past natural events recorded by vestigial forms of perturbed landscapes. There is little sense in establishing a suburban subdivision on a hillside showing abundant evidence of landsliding. Better that the area be declared public property to be used as a park with easily repairable riding and walking trails. In terms of history, perturbed landscapes are the ones with the richest story to tell. To read that story correctly and with perception, it is necessary to know what an unperturbed landscape looks like—hence, the need for understanding of the elements of landscape evolution.

ROLE OF CATASTROPHES

The impact of catastrophic events on landscapes can be scenically dramatic: a single landslide can scar a hillside, dam a river, and create a lake which subsequently devastatingly floods the downstream country when the insecure landslide dam partly or wholly collapses (Fig. 7). A large slide on the Gros Ventre River, just east of Jackson Hole (Wyoming), is an historical (1925) example of just such a sequence (169). Although spectacular, the question remains as to what degree catastrophes influence, control, or impact normal landscape evolution. The answer varies with the situation.

What constitutes a catastrophe in geological terms, not in terms of its impact on mankind and his works? A geological catastrophe, for our purposes, can be regarded as something that happens quickly, does not recur periodically, and produces significant morphological change, either in terms of scale or types of features. Climatic change can be catastrophic, in a human sense, but its geological effects are more evolutionary in nature. The matter of recurrence interval has been addressed (37, 170–172) in terms of fluvial events such as floods. Are the 1-year, 10-year, and 100-year floods of a river system all geological catastrophes, or does the separation come between the 10-year and 100-year floods? It depends upon the point of view and a definitive answer has not yet been given, although the principle of threshold is clearly a factor (171, 173). The power of catastrophic events to accomplish work is impressive—the geological work of a 100-year flood can exceed, in terms of landforms at least, the cumulative effects of a preceding century of normal runoff. Alteration of marine shorelines by hurricane-generated waves is another example (4, 174). Geological catastrophes are a little like rattlesnakes. One can occasionally be fooled by the chirpings of a cricket, but the rattling of the real article is instinctively and unquestionably recognized as genuine.

In some instances, geological catastrophes impose an indelible imprint on a landscape. Because no landscape is permanent, such an imprint may be eventually erased or obscured, but a catastrophe can mark the landscape for a significant part of its history. An example would be the channeled scablands of eastern Washington created by the Spokane Flood (110), a gigantic discharge of glacial meltwaters loosened by the collapse of a large ice dam. The features created by this flood are of such large scale and unusual geometry that they are clearly exotic in terms of normal landscape forms. They dominate the region, giving it a unique appearance, even on Landsat photo images taken from hundreds of kilometers above. A meteoroidal impact by a kilometer-size body would constitute a geological catastrophe for the impact site and its immediate vicinity. Meteor Crater (Arizona) is the best example in the United States, but the effects of older, larger impacts are not to be overlooked (161).

Volcanic eruptions, especially those of explosive character, have catastrophically and repeatedly altered the landscape of many parts of the world, within historical times, as residents of southwest Washington state have been able to testify since the May 18, 1980, blast of Mt. St. Helens. Events related to volcanic activity are probably the most frequent and widespread of all natural geological catastrophes, and they have played a major role in shaping regional landscapes on many parts of the global surface.

Schumm (168) has shown that tectonic activity can far exceed rates of erosion, so that tectonism usually interrupts the progression of a normal cycle of erosion by a degree large enough to initiate an entirely new cycle. A recent book on landforms

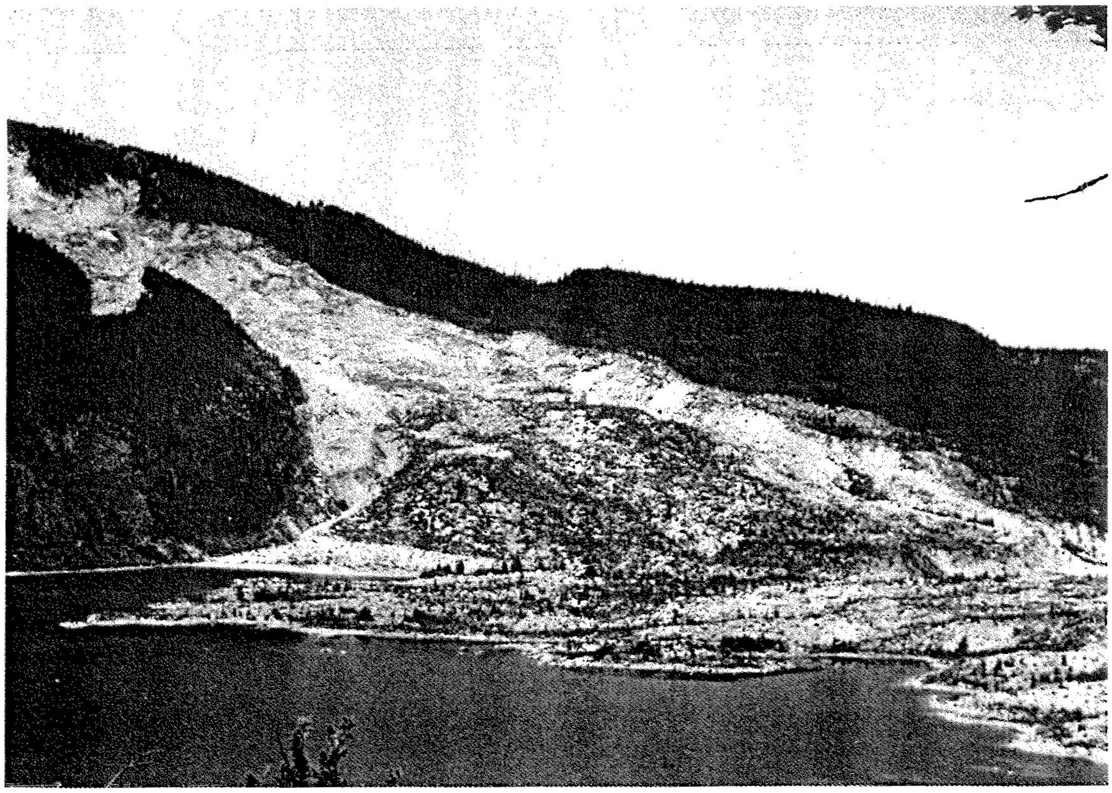

FIG. 7. The 1925 Gros Ventre Landslide (Wyoming), a catastrophic scarring of the landscape. Water-level line, higher by about 50 feet, is faintly visible above present lake to left.

of Japan (4) takes the position that most of the Japanese landscapes are dominated by the effects of geological catastrophes: volcanic eruptions, landslides, faulting, warping, and meteorological events such as typhoons. The role of catastrophes in shaping landscapes in other equally dynamic regions deserves a more integrated treatment than it has so far received.

WHITHER TOMORROW?

What would be worth doing next in studying the evolution of slopes? One answer is to return to the field, the natural laboratory, to seek further empirical data. A focus of attention upon the nature and behavior of the regolith (17, 20, 42, 57, 175–178) on mantled slopes would seem a reasonable way to go.

We need further information on variations of the thickness of the regolith on different slope reaches and on different slope elements or forms. Variations in its character as affected by inhomogeneities of the underlying substrate should receive attention, and the changes, particularly of grain size, if any, occurring within a mantle upon a homogeneous substrate are not fully understood (19, 57). Mass mobility of the mantle on different parts of a slope is clearly an important parameter worthy of further study (42, 179, 180). The problem of regolithic creep should be considered within the context of the total discharge of debris passing over various reaches of a slope. In fact, slopes could be analyzed in terms of debris discharge and the various parameters and factors influencing discharge. Resistance of the regolith to surface wash is also a factor of importance (21, 42, 73, 175, 180). The infiltration rates of different regoliths merit more attention, and the role of subsurface water throughflow (42, 68) provided by such infiltration, especially in terms of lateral movement of particulate material by eluviation (20, 42, 81, 181, 182) in a downslope direction, needs more evaluation.

One answer to the rhetorical title of this section is "back to the field and look at the regolith." We should also recognize that slopes and the landforms they compose are delicately adjusted to each other, in the closed basins of arid regions (183) as well as in the integrated drainage basins of humid regions (184).

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